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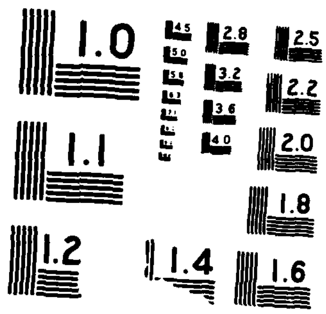
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REPORT NO. NADC-87169-60



# AGARD ENGINE DISC MATERIAL COOPERATIVE TEST (SUPPLEMENTARY PROGRAM)

Eun U. Lee

Air Vehicle and Crew Systems Technology Department

NAVAL AIR DEVELOPMENT CENTER

Warminster, Pennsylvania 18974



12 AUGUST, 1987

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Prepared for

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Warminster, Pennsylvania 18974

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

From a gas turbine engine compressor spool of Ti-17 alloy, cylindrical unnotched specimens and flat double edge notched specimens were machined and fatigue-tested. The flat double edge notched specimens were also subjected to electrical potential drop measurements. The microstructure and fracture surface morphology of the representative specimens were examined.

The variation of fatigue life, N, with applied stress range, $\Delta\sigma$, was described by an equation of the form $\log N = a + b\Delta\sigma$. The variation of normalized crack voltage, $(V/V_O)/(V_R/V_{R_o})$, with normalized crack length, (a/w), was given by an equation of the form $(V/V_O)/(V_R/V_{R_o}) = A + A_1(a/w) + A_2(a/w)^2 + A_3(a/w)^3$.

This investigation was a part of the NATO's AGARD Engine Disc Material Cooperative Test Project.

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## INTRODUCTION

The AGARD (Advisory Group for Aerospace Research and Development) engine disc material cooperative test program is a joint task of the NATO member laboratories to characterize the fatigue cracking and fracture behavior of aircraft gas turbine engine discs. The basic knowledge on the fatigue and fracture is essential for formulating a reliable prediction methodology for aircraft gas turbine engine disc life.

This program consists of two phases. The first phase, CORE project, was aimed at test and specimen standardization and calibration of the different laboratories. It was completed in 1986 and the NADC portion of the work was reported[1] previously. The second phase, SUPPLEMENTARY project, addresses the parameters relevant for real service operation: mission loading, sequence and dwell effects, temperature, fatigue threshold, etc. As a portion of the SUPPLEMENTARY project, NADC investigated the fatigue behavior, electrical potential change with crack growth, microstructure, and fractograph of the specimens from a gas turbine engine compressor spool of Ti-17 alloy. Experimental details of this investigation and the results are presented in this report.

## EXPERIMENTAL PROCEDURE

The experimental procedure includes Material and Specimen Preparation, Microstructural Examination, Fatigue Tests, Electrical Potential Drop Crack Measurement, Visual Measurement of Crack Size, and Fractographic Examination.

### MATERIAL AND SPECIMEN PREPARATION

A Ti-17 alloy taken from a compressor spool of an aircraft gas turbine engine was selected as the specimen material for the SUPPLEMENTARY project of the AGARD program. From the compressor spool, (figure 1), two types of specimens, cylindrical unnotched specimens and flat double edge notched specimens, were machined at National Aeronautical Establishment, Ottawa, Canada, (figures 2 and 3). The nominal chemical composition of the Ti-17 alloy is shown in table 1.

### MICROSTRUCTURAL EXAMINATION

A specimen plane, parallel to the crack plane, was polished, etched by Keller's reagent, and examined in an optical microscope.

### FATIGUE TESTS

The fatigue tests were conducted at room temperature in laboratory atmosphere using a closed-loop electro-hydraulic MTS machine. The test conditions were stress ratio ($\sigma_{min}/\sigma_{max}$) of 0.1, constant amplitude loading of trapezoidal waveform (figure 4), and frequencies of 2.5 Hz for the cylindrical unnotched specimens and 0.25 Hz for the flat double edge notched specimens.

### ELECTRICAL POTENTIAL DROP CRACK MEASUREMENT

For the measurement of the electrical potential drop accompanying crack growth in the flat double edge notched specimen, titanium wire potential probes of 0.5 mm dia. were spot-welded at the opposite corners of each specimen notch, (figure 5). Separate leads of titanium wire were also spot-welded on a flat double edge notched specimen of Ti-6Al-4V alloy with an identical dimension, which served as a reference block. A

Hughes Aircraft Stored Energy Welding Power Supply, Model VTW-31B, was used for the spot-welding. The input and output leads of titanium wire were connected to a DC Supply and a Micro Volt-Ammeter, respectively, (figure 6). Prior to the electrical potential drop measurement, the specimen and the MTS machine frame were electrically insulated by Bakelite washers.

A constant D.C. current, ~6.0A, was passed through the specimen and the electrical potential over the crack plane was measured by two probes located on both sides of the crack. In addition, a voltage in the reference block was measured to account for the temperature effects and current variation.

## VISUAL MEASUREMENT OF CRACK SIZE

When a crack became visible on a surface of the flat double edge notched specimen, the fatigue loading was stopped, and the crack length from the notch was measured using a travelling telescope. The measurement was repeated until the specimen fractured.

## FRACTOGRAPHIC EXAMINATION

The fractographic examination of fatigue-fractured specimens was carried out using an Advanced Metals Research (AMR) 1000 Scanning Electron Microscope, operated at an accelerating voltage of 20 kv.

## RESULTS AND DISCUSSION

The results and discussion are divided into four parts: Cylindrical Unnotched Specimen Tests, Flat Double Edge Notched Specimen Tests, Microstructure, and Fractography.

### CYLINDRICAL UNNOTCHED SPECIMEN TESTS

In the fatigue tests of the cylindrical unnotched specimens, the applied stress ranges were 750, 850, and 950 MPa. The stress range, $\Delta\sigma$ (MPa), and the corresponding number of fatigue cycles to fracture (fatigue fracture life), $N_f$, are tabulated in table 2 and plotted in figure 7. The plot is a straight line and defined by the equation.

$$\Delta\sigma = 1328 - 90 \log N_f$$

or $$\log N_f = 14.76 - 0.01\Delta\sigma$$

For a given stress range, the fatigue fracture life of the Ti-17 alloy specimen from a compressor spool is about two orders of magnitude longer than that of the Ti-6Al-4V alloy specimen from a fan disc in the CORE project[1] of this AGARD program. The comparison is also shown in figure 7.

### FLAT DOUBLE EDGE NOTCHED SPECIMEN TESTS

In the fatigue tests of the flat double edge notched specimens, the stress ranges were 475, 625, and 775 MPa. During each fatigue test, the electrical potential over the crack plane and the increasing crack length were measured.

The normalized crack voltage, $(V/V_O)/(V_R/V_{R_O})$, is taken in this study as the measure of the electrical potential over the crack plane, where

$V_o$ : specimen voltage at the start of the test (crack length $a = 0$)

$V$ : specimen voltage

$V_{R_o}$ : reference voltage at the start of the test

$V_R$ : reference voltage

In the intitial stage of crack growth, the normalized crack voltage gradually increases with increasing number of fatigue landing cycles. In the final stage of crack growth, the increase is much steeper. A similar change is also observable on the side of the notch with no visible crack. In such a case, the magnitude of the normalized crack voltage is smaller than that on the side of the notch with a visible crack. These changes are shown in figures 8-12 and can be described by the following equations, respectively.

Specimen No.1:

$$(V/V_O)/(V_R/V_{R_o}) = 0.6797 + 6.0719(a/w) - 29.8160(a/w)^2 + 57.3172(a/w)^3$$

Specimen No.2:

$$(V/V_O)/(V_R/V_{R_o}) = 1.3037 + 0.1718(a/w) + 3.4886(a/w)^2 + 2.8947(a/w)^3$$

Specimen No.4:

$$(V/V_O)/(V_R/V_{R_o}) = 0.9927 + 0.4226(a/w) - 3.4603(a/w)^2 + 21.8985(a/w)^3$$

Specimen No.5:

#1 Notch Side:

$$(V/V_O)/(V_R/V_{R_o}) = 1.2438 - 12.9729(a/w) + 213.9109(a/w)^2 - 1{,}014.2521(a/w)^3$$

#2 Notch Side:

$$(V/V_O)/(V_R/V_{R_o}) = 1.1690 - 7.4328(a/w) + 147.7939(a/w)^2 - 763.3036(a/w)^3$$

The length change of the crack, emanating from a notch, as a function of the number of fatigue loading cycles is similar to the change of the normalized crack voltage. This is shown in figures 13-16.

The increase of the normalized crack voltage with the normalized crack length is shown in figures 17-20. The normalized crack length is defined as a/w, where a is the crack length from a notch and w the width between the two edge notches.

From the plot of the normalized crack voltage vs the number of fatigue loading cycles, the particular number of fatigue loading cycles at which the normalized crack voltage is 1% higher than the initial value is taken as the fatigue crack initiation life $N_i$. This was suggested in the AGARD Working Document for this project[2]. The applied stress range, $\Delta\sigma$, and the corresponding fatigue crack initiation life, $N_i$, and the fatigue fracture life, $N_f$, are tabulated in table 3 and plotted in figures 21 and 22. These plots are straight lines and are defined by the following equations, respectively.

$$\Delta\sigma = 3037 - 594 \log N_i$$

or $$\log N_i = 5.11 - 0.002\Delta\sigma$$

$$\Delta\sigma = 2557 - 468 \log N_f$$

or $$\log N_f = 5.46 - 0.002\Delta\sigma$$

The fatigue crack initiation life and the fatigue fracture life of the Ti-17 alloy specimen are greater than those of the Ti-6Al-4V alloy specimen[1] at the higher stress ranges but close to those at the lower stress range, (figures 21 and 22).

For a given stress range, the fatigue fracture life of the flat double edge notched specimen is shorter than that of the cylindrical unnotched specimen, (figure 22). The reduction in the fatigue fracture life due to the double edge notches is greater in Ti-17 alloy than in the Ti-6Al-4V alloy[1]. In this study, the fatigue-life reduction factor or fatigue-notch factor, $K_f$, is defined as the ratio of the stress range of the unnotched specimen to that of the notched specimen at a specified number of fatigue loading cycles. The $K_f$ values of the Ti-17 alloy are 1.41, 1.73, and 2.00, whereas those of the Ti-6Al-4V alloy[1] are 1.31, 1.42, and 1.48, at 10,000, 20,000 and 30,000 fatigue loading cycles, respectively, (table 4). This indicates that the fatigue-notch sensitivity of the Ti-17 alloy is 8 ~ 35% greater than that of the

Ti-6Al-4V alloy, although the fatigue resistance of the former is greater than that of the latter in the test of cylindrical unnotched specimens.

## MICROSTRUCTURE

The optical micrographs of the cylindrical unnotched specimen and the flat double edge notched specimen are shown in figures 23(a) and (b), respectively. The microstructure consists of alpha at prior beta grain boundaries and transformed beta containing acicular alpha.

## FRACTOGRAPHY

Each fractograph of the fatigue-fractured cylindrical unnotched specimen and the flat double edge notched specimen shows a slow crack growth area of thumb-nail shape along the outside diameter (O.D.) surface or one of the notches and an overload fracture area, (figures 24 and 25). From the fracture surface morphology, the fatigue crack initiation site can be located at a point on the O.D. surface of the cylindrical unnotched specimen or one notch of the flat double edge notched specimen. In the vicinity of the crack initiation site, cleavage facets are visible, and in the rest of the slow crack growth area, patches of fatigue striations are noticeable. The overload fracture area contains separated-grain facet and shear-lips regions. The grain facets and shear-lip exhibit dimples. Apparently, intergranular fracture and microvoid coalescence takes place during the overload fracture in this material. Such an intergranular fracture was not detectable during the overload fracture in the Ti-6Al-4V alloy specimen from a fan disc in the CORE project.[1]

SUMMARY

1. From a gas turbine engine compressor spool of Ti-17 alloy, two groups of specimens: cylindrical unnotched specimens and flat double edge notched specimens were machined and fatigue-tested. The flat double edge notched specimens were also subjected to electrical potential drop measurement. The microstructure and fracture surface morphology of the representative specimens were examined.

2. The variation of the fatigue crack initiation life, $N_i$, and the fatigue fracture life, $N_f$, with the applied stress range, $\Delta\sigma$, can be described by the following equations.

Cylindrical Unnotched Specimen:

$$\log N_f = 14.76 - 0.01\Delta\sigma$$

Flat Double Edge Notched Specimen:

$$\log N_i = 5.11 - 0.002\Delta\sigma$$

$$\log N_f = 5.46 - 0.002\Delta\sigma$$

3. In the flat double edge notched specimens, the normalized crack voltage increases with the number of fatigue loading cycles sluggishly in the initial stage of crack growth and rapidly in the final stage of crack growth. A similar feature is also seen in the change of crack length with the number of fatigue loading cycles. The change of the normalized crack voltage with the normalized crack length can be described by the equation of the form

$$(V/V_O)/(V_R/V_{R_O}) = A + A_1(a/w) + A_2(a/w)^2 + A_3(a/w)^3$$

where

$V_O$ : specimen voltage at the start of the test (crack length = 0)

$V$ : specimen voltage

$V_{R_0}$ : reference voltage at the start of the test

$V_R$ : reference voltage

a : crack length

w : specimen width

$A, A_1, A_2, A_3$ : constants, which change with specimen

4. The microstructure of the specimens consists of alpha at prior beta grain boundaries and transformed beta containing acicular alpha.

5. The fractographs of the specimens show cleavage facets and fatigue striations within the slow crack growth area and intergranular fracture surfaces and shear-lips with dimples in the overload fracture area.

6. Compared to the Ti-6Al-4V alloy of the CORE project, the Ti-17 alloy shows better fatigue resistance in the unnotched specimen test but greater fatigue-notch sensitivity in the notched specimen test.

## REFERENCES


1. Lee, Eun U, "AGARD Engine Disc Material Cooperative Test," Report No. NADC-86045-60, 31 March 1986. AD A175533

2. Mom, A.J.A., "Working Document for the AGARD Cooperative Test Programme on Titanium Alloy Engine Disc Material," NLR TR 84022 L, National Aerospace Laboratory NLR, The Netherlands, March 20, 1984.

Table 1. Chemical Composition of Ti-17 Alloy

| | Weight Percent | |
|---|---|---|
| Element | Minimum | Maximum |
| Al | 4.5 | 5.5 |
| Sn | 1.5 | 2.5 |
| Zr | 1.5 | 2.5 |
| Mo | 3.5 | 4.5 |
| Cr | 3.5 | 4.5 |
| O | 0.08 | 0.13 |
| N | — | 0.04 |
| H | — | 0.0125 |
| Fe | — | 0.30 |
| Ti | Balance | |

Table 2. Applied Stress Range and Corresponding Fatigue Fracture Life in Cylindrical Unnotched Specimen

| Specimen No. | Stress Range $\Delta\sigma$ (MPa) | Fatigue Fracture Life $N_f$ (cycle) |
|---|---|---|
| 1 | 750 | 1,851,300 |
| 2 | 750 | 1,460,560 |
| 3 | 850 | 377,240 |
| 5 | 850 | 472,885 |
| 4 | 950 | 14,450 |
| 6 | 950 | 12,410 |

Table 3. Applied Stress Range and Corresponding Fatigue Crack Initiation Life and Fatigue Fracture Life in Flat Double Edge Notched Specimen

| Specimen No. | Stress Range $\Delta\sigma$ (MPa) | Fatigue Crack Initiation Life $N_i$ (cycle) | Fatigue Fracture Life $N_f$ (cycle) |
|---|---|---|---|
| 1 | 475 | — | 30,088 |
| 2 | 475 | 18,500 | 23,643 |
| 3 | 625 | — | 10,456 |
| 4 | 625 | 13,100 | 16,738 |
| 5 | 775 | 5,700 | 6.212 |
| 6 | 775 | 7,200 | 7,566 |

Table 4. Fatigue - Notch factors, $K_f$, of Ti-17 and Ti-6Al-4V Alloys

| Fatigue Fracture Life, $N_f$ (cycle) | Stress Range (MPa) Cylindrical Specimen $(\Delta\sigma_c)_{Ti\,17}$ | $(\Delta\sigma_c)_{Ti\,64}$ | Flat Notched Specimen $(\Delta\sigma_f)_{Ti\,17}$ | $(\Delta\sigma_f)_{Ti\,64}$ | $K_f = \Delta\sigma_c/\Delta\sigma_f$ Ti-17 | Ti-6-4 | $\left[\frac{(K_f)_{Ti\,17}}{(K_f)_{Ti\,64}}\right]$ |
|---|---|---|---|---|---|---|---|
| 10,000 | 966 | 781 | 685 | 597 | 1.41 | 1.31 | 1.08 |
| 20,000 | 941 | 753 | 544 | 532 | 1.73 | 1.42 | 1.22 |
| 30,000 | 925 | 737 | 462 | 498 | 2.00 | 1.48 | 1.35 |

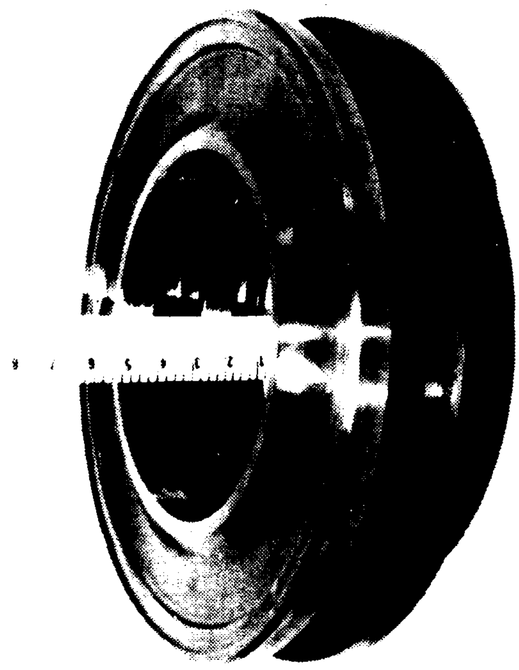


Figure 1. Compressor Spool

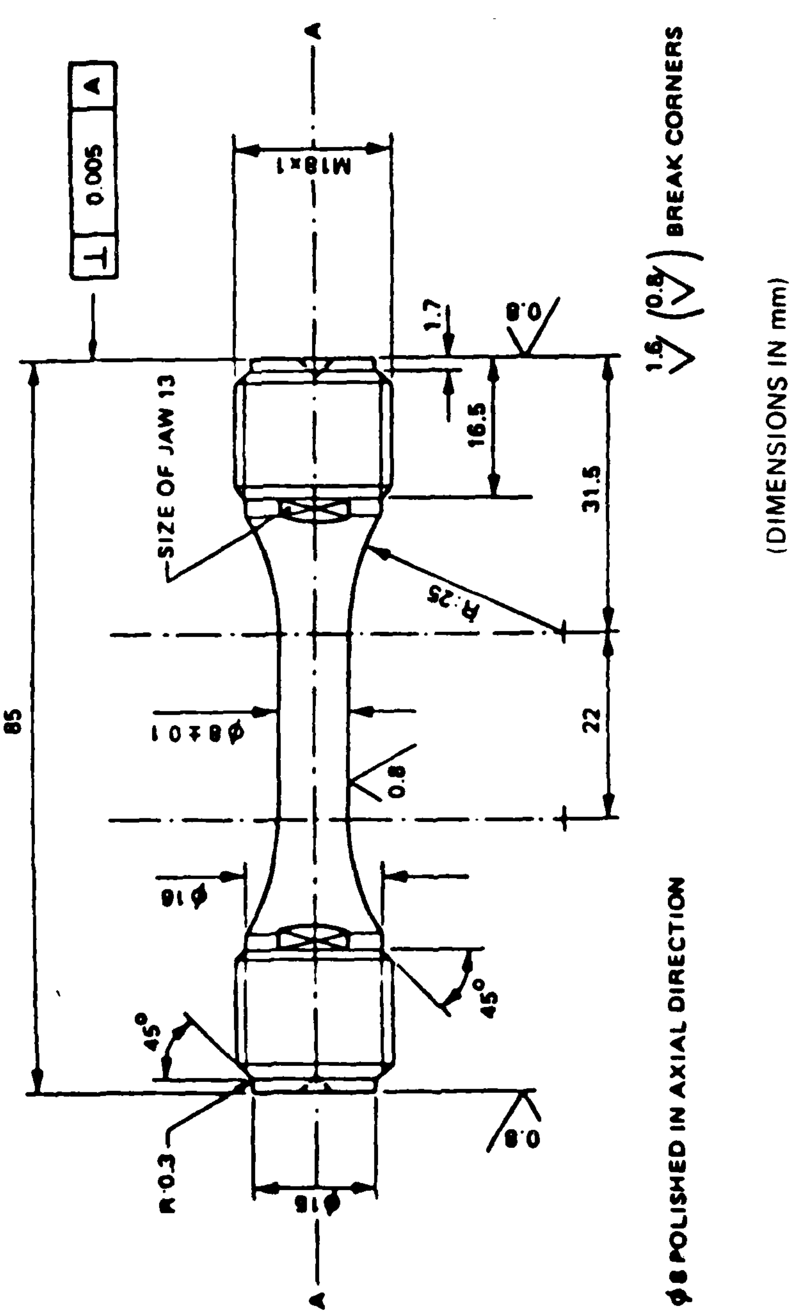



Figure 2. Cylindrical Unnotched Specimen

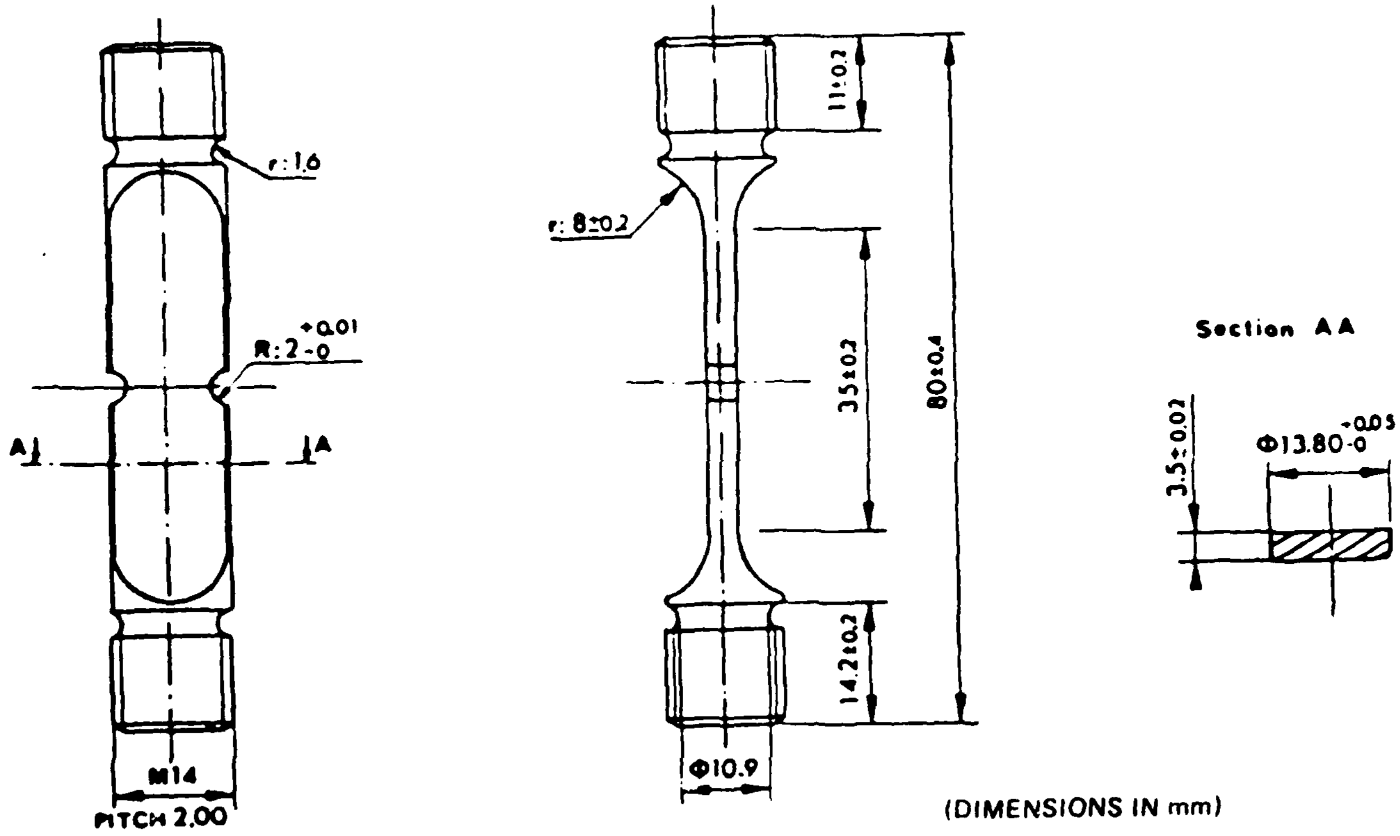



Figure 3. Flat Double Edge Notched Specimen

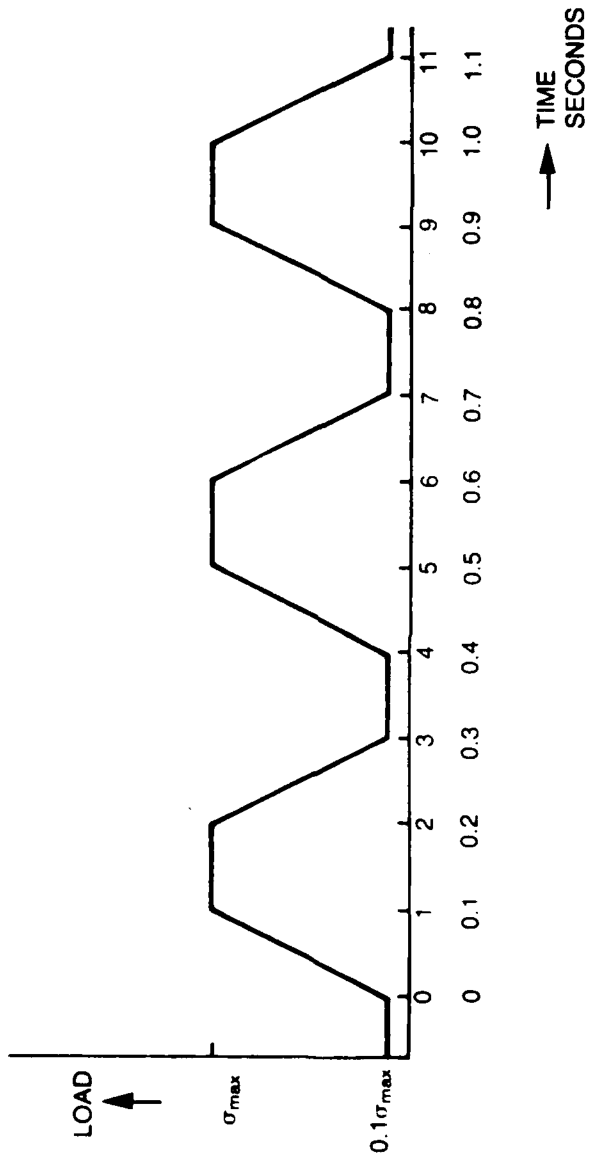



Figure 4. Trapezoidal Load Waveform

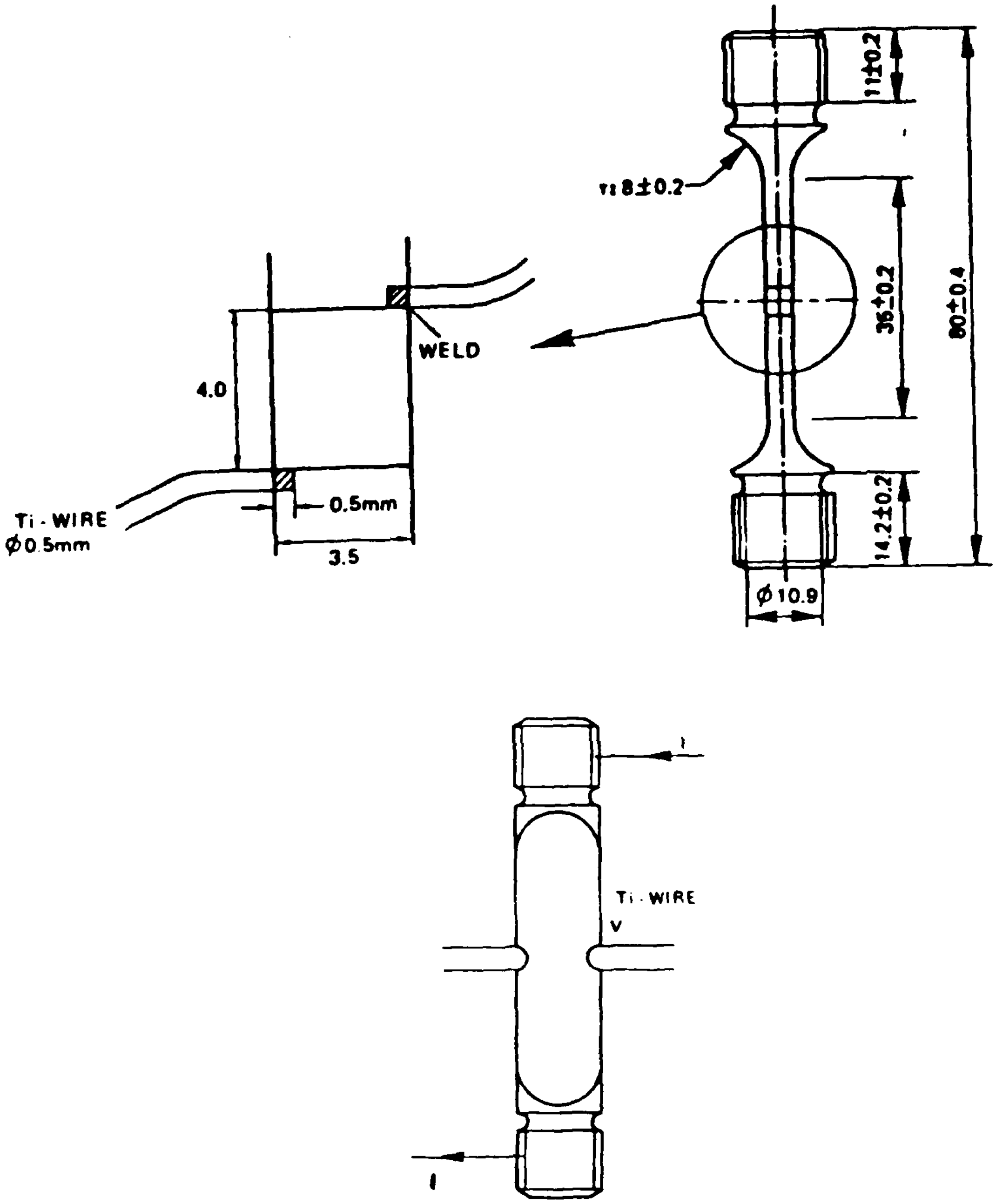



Figure 5. Attachment of Potential Leads and Set-Up of Wiring — Flat Double Edge Notched Specimen

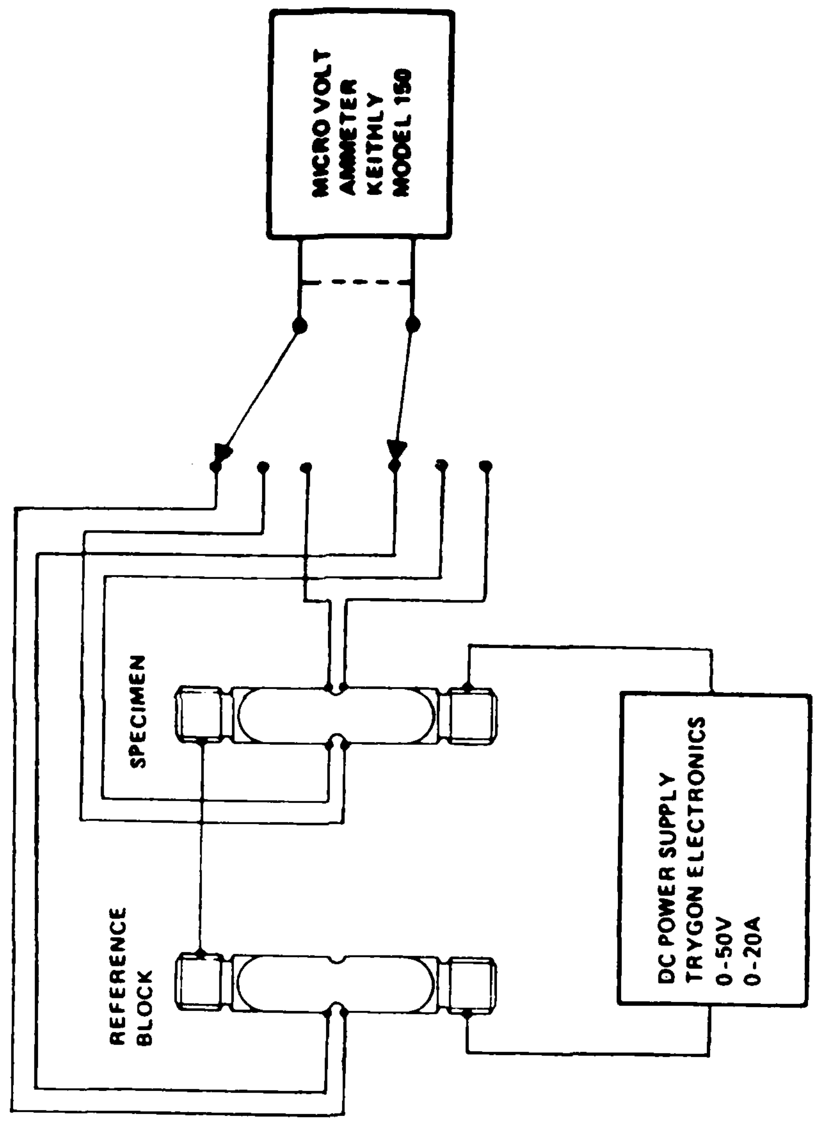



Figure 6. Set-Up for Electrical Potential Drop Measurement

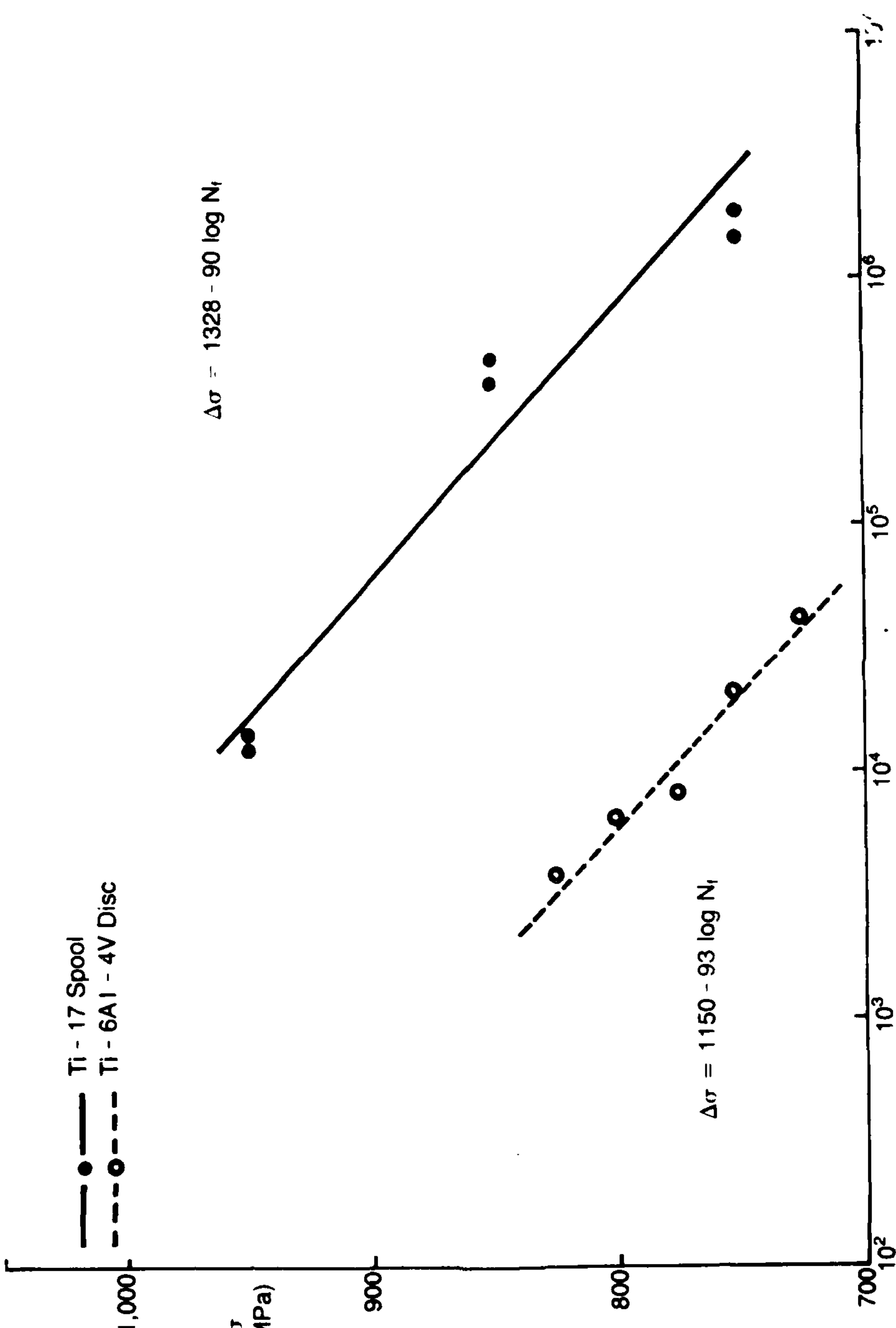



Figure 7. Applied Stress Range and Corresponding Fatigue Fracture Life in Cylindrical Unnotched Specimen

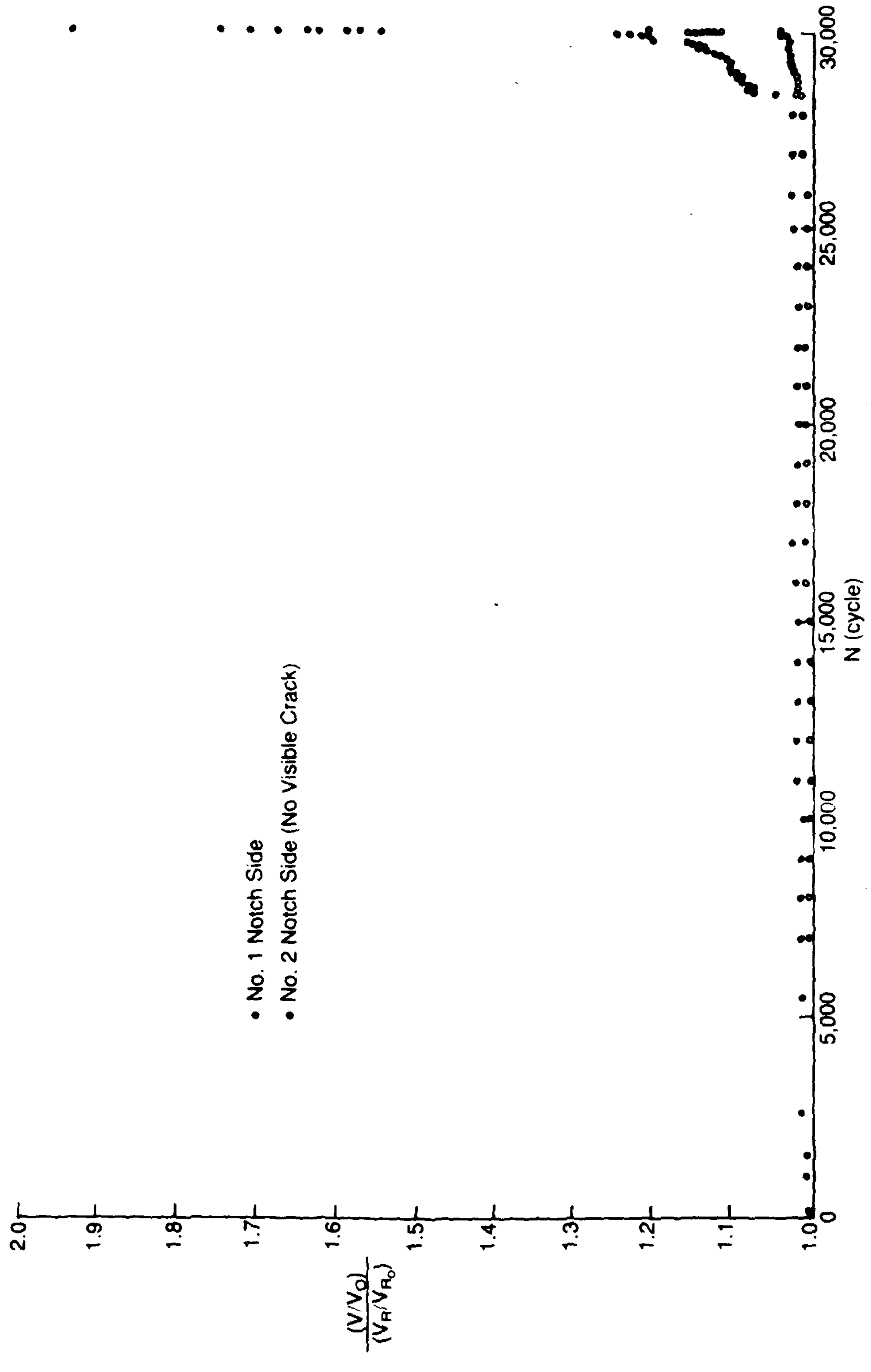



Figure 8. Change of Normalized Crack Voltage with Number of Fatigue Loading Cycles in Flat Double Edge Notched Specimen No. 1 ($\Delta\sigma$ = 475 MPa)

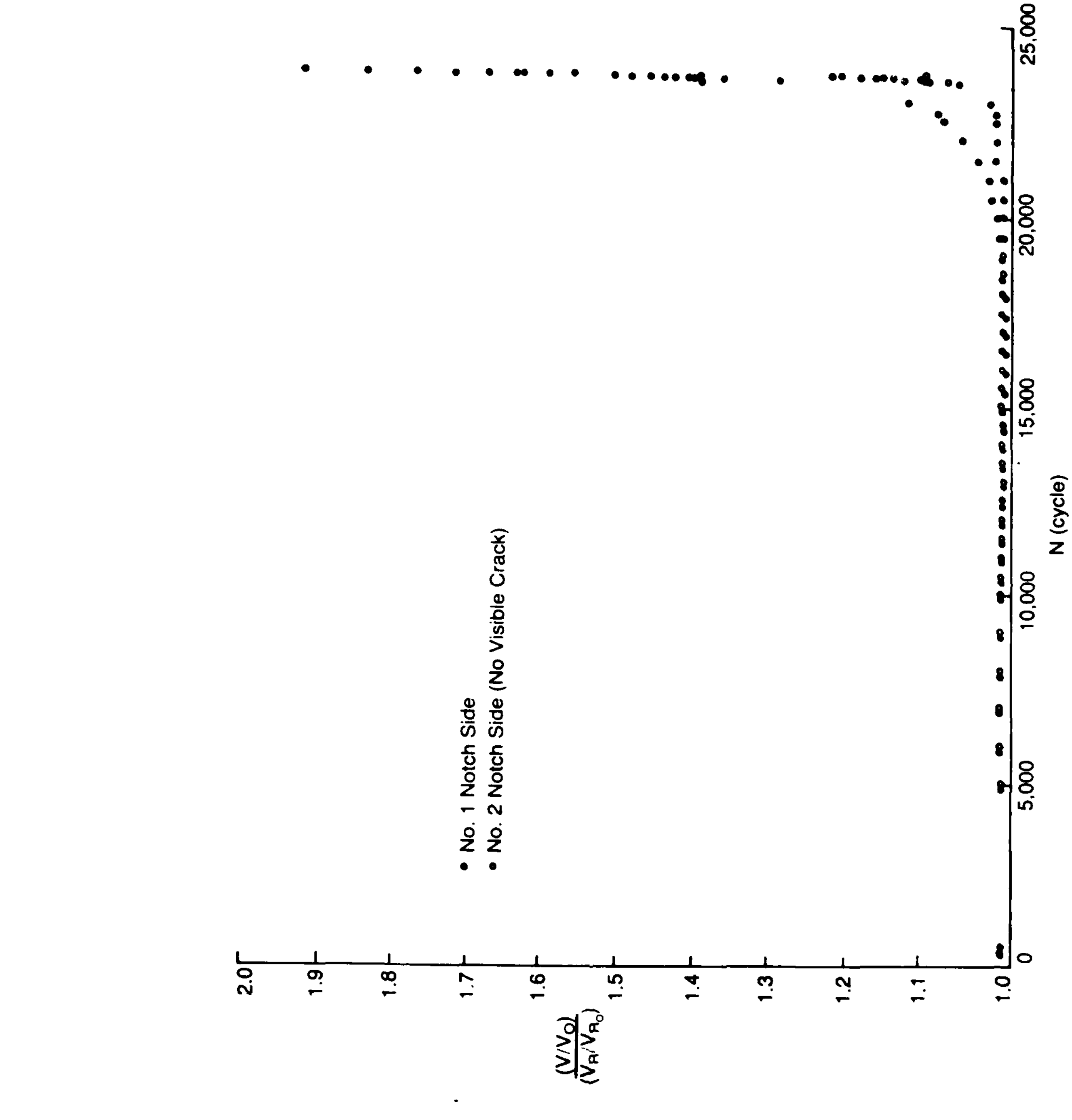



Figure 9. Change of Normalized Crack Voltage with Number of Fatigue Loading Cycles in Flat Double Edge Notched Specimen No. 2 ($\Delta\sigma$ = 475 MPa)

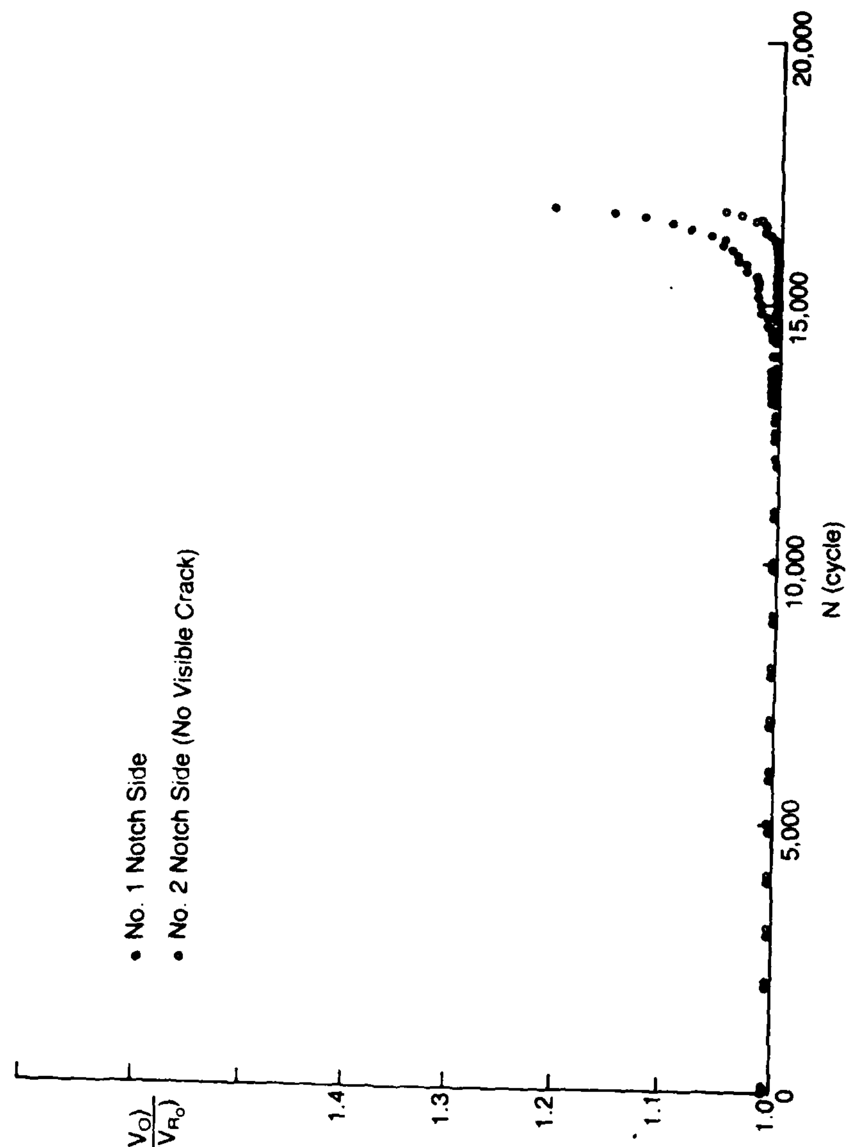



Figure 10. Change of Normalized Crack Voltage with Number of Fatigue Loading Cycles in Flat Double Edge Notched Specimen No. 4 ($\Delta\sigma$ = 625 MPa)

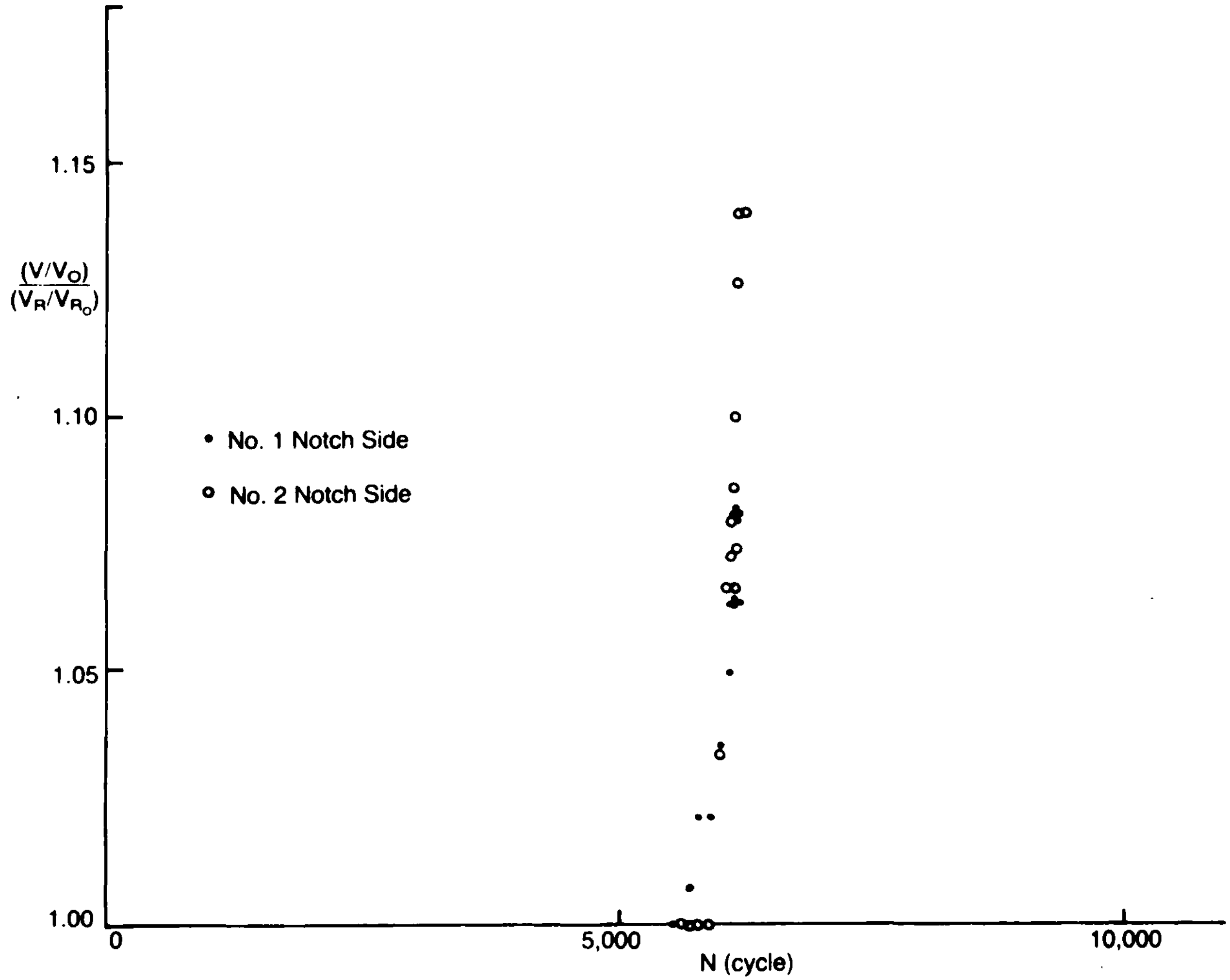



Figure 11. Change of Normalized Crack Voltage with Number of Fatigue Loading Cycles in Flat Double Edge Notched Specimen No. 5 ($\Delta\sigma$ = 775 MPa)

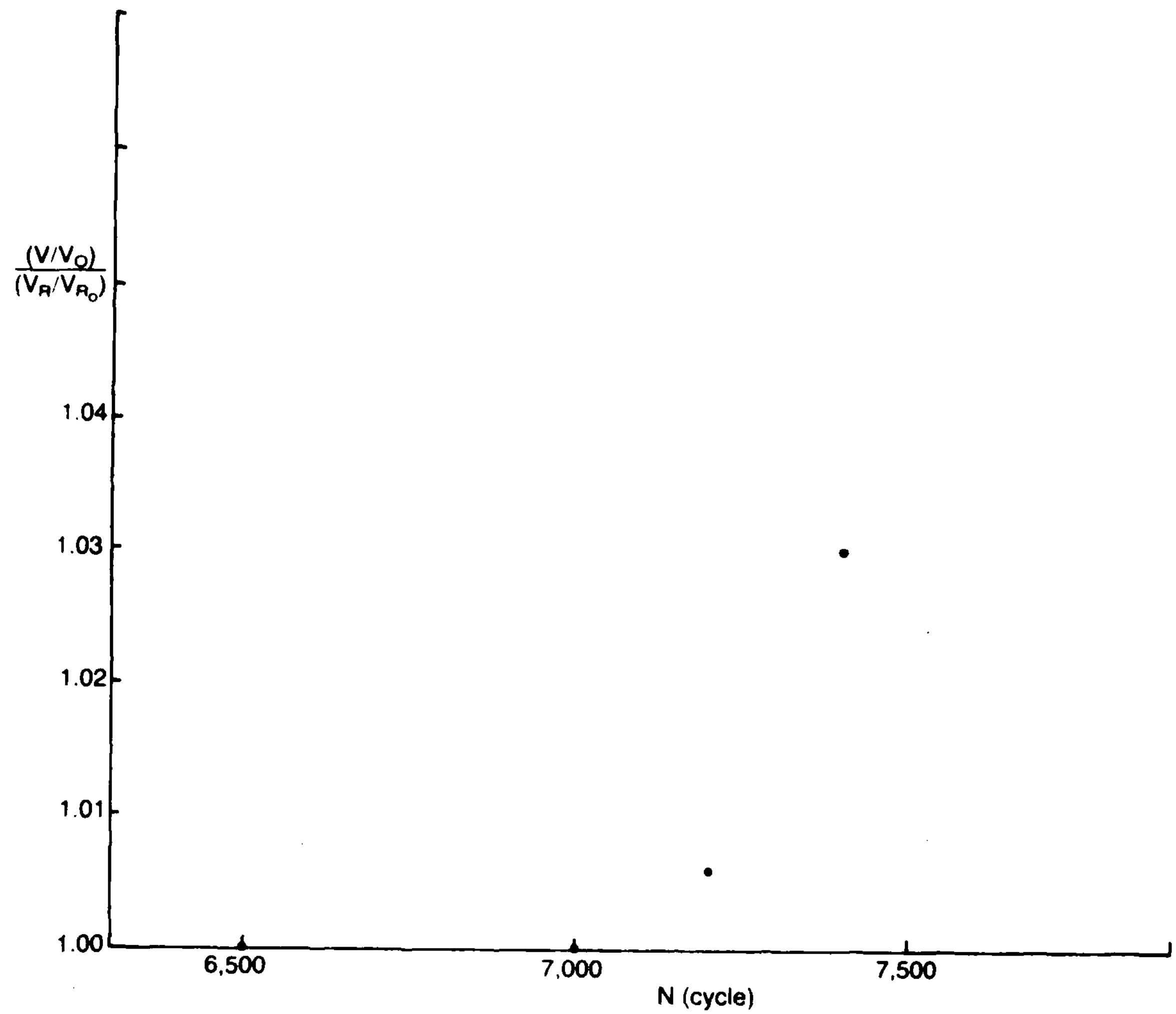



Figure 12. Change of Normalized Crack Voltage with Number of Fatigue Loading Cycles in Flat Double Edge Notched Specimen No. 6 ($\Delta\sigma$ = 775 MPa)

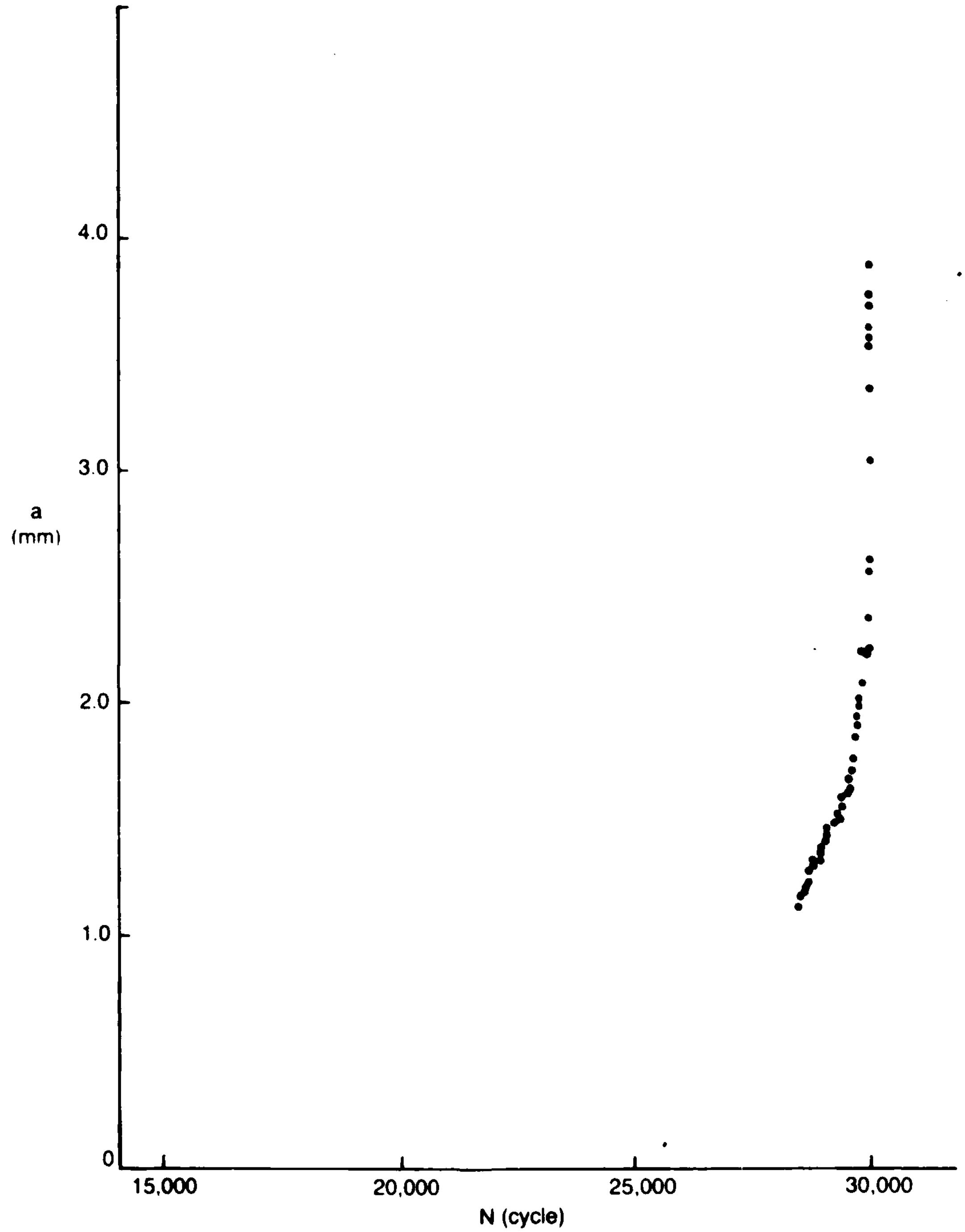



Figure 13. Change of Crack Length with Number of Fatigue Loading Cycles in Flat Double Edge Notched Specimen No. 1 ($\Delta\sigma$ = 475 MPa)

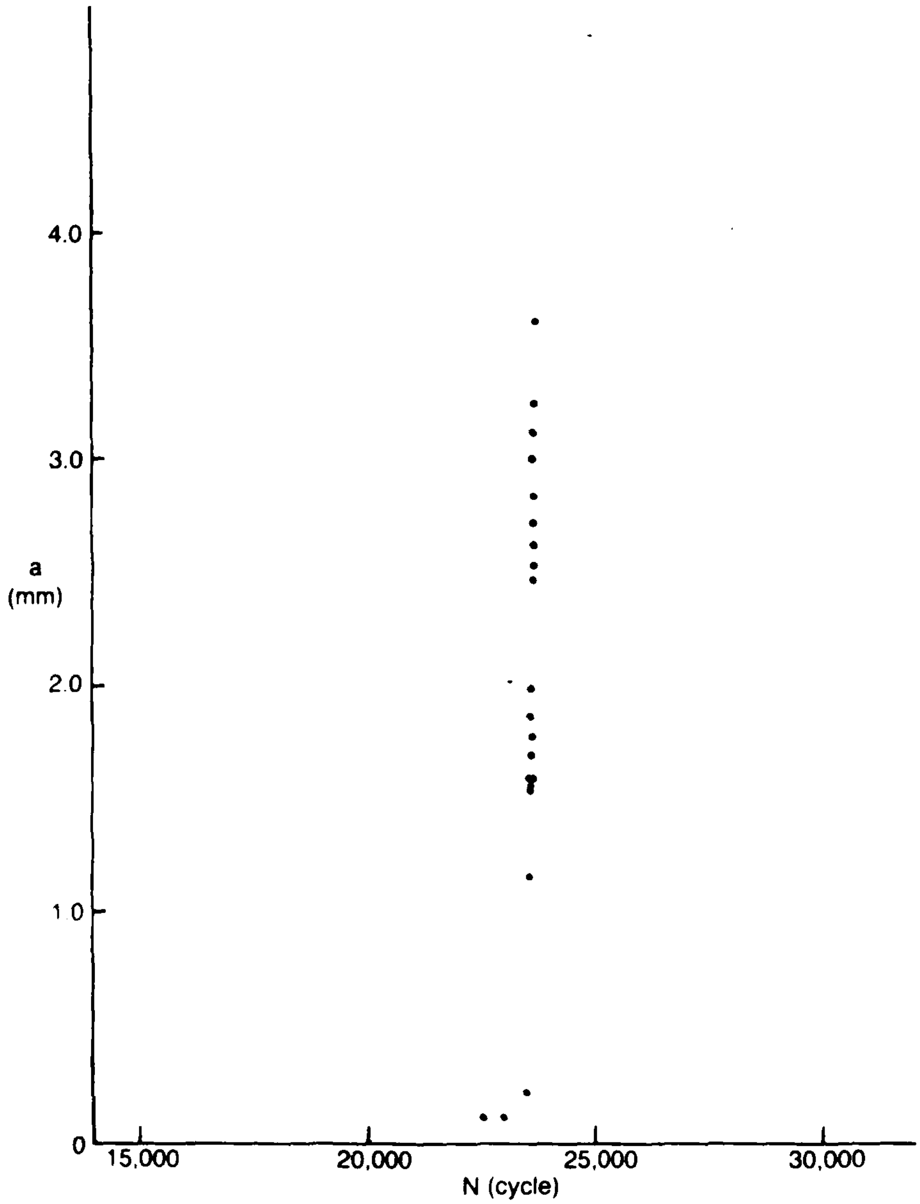



Figure 14. Change of Crack Length with Number of Fatigue Loading Cycles in Flat Double Edge Notched Specimen No. 2 ($\Delta\sigma$ = 475 MPa)

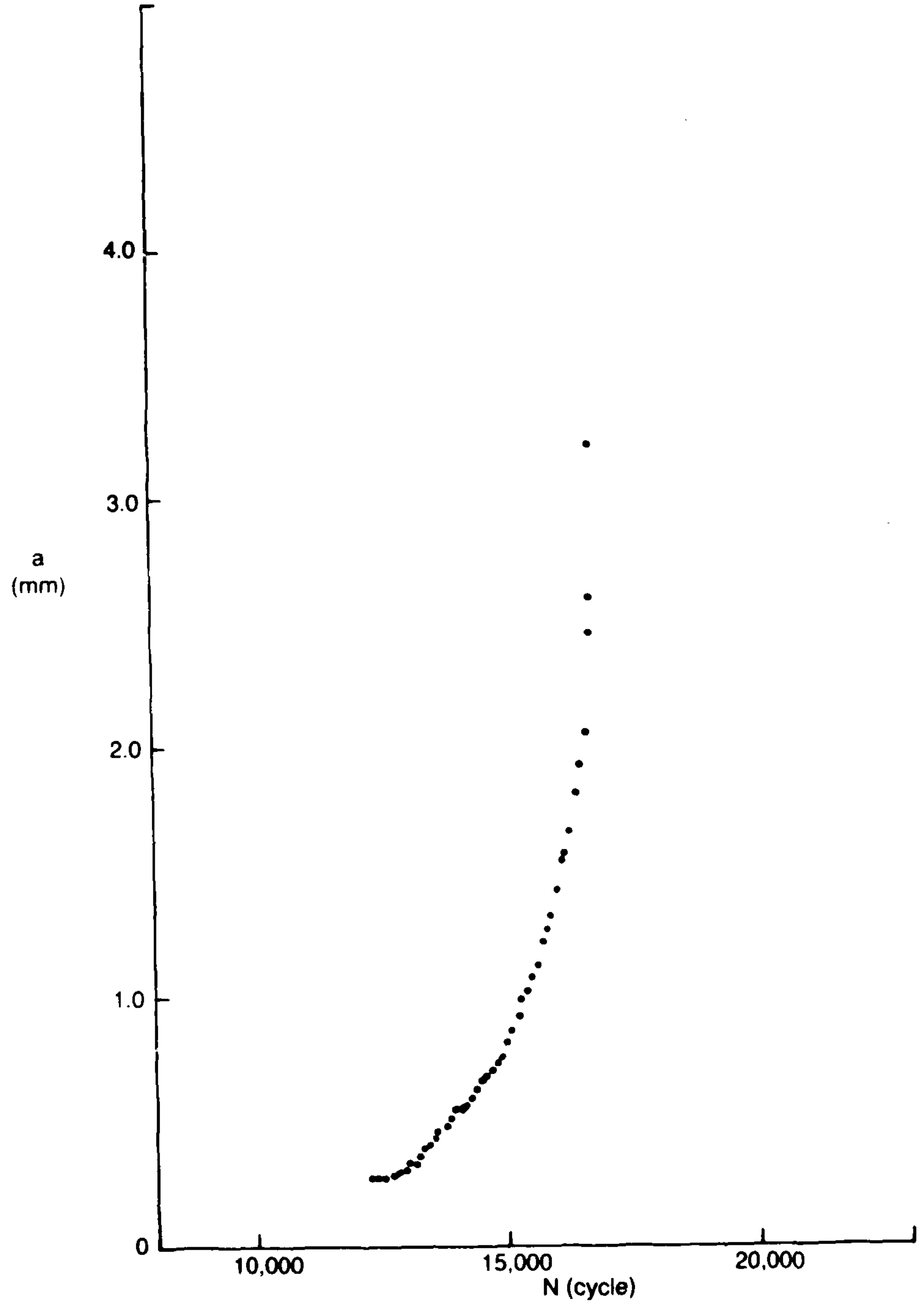



Figure 15. Change of Crack Length with Number of Fatigue Loading Cycles in Flat Double Edge Notched Specimen No. 4 ($\Delta\sigma$ = 625 MPa)

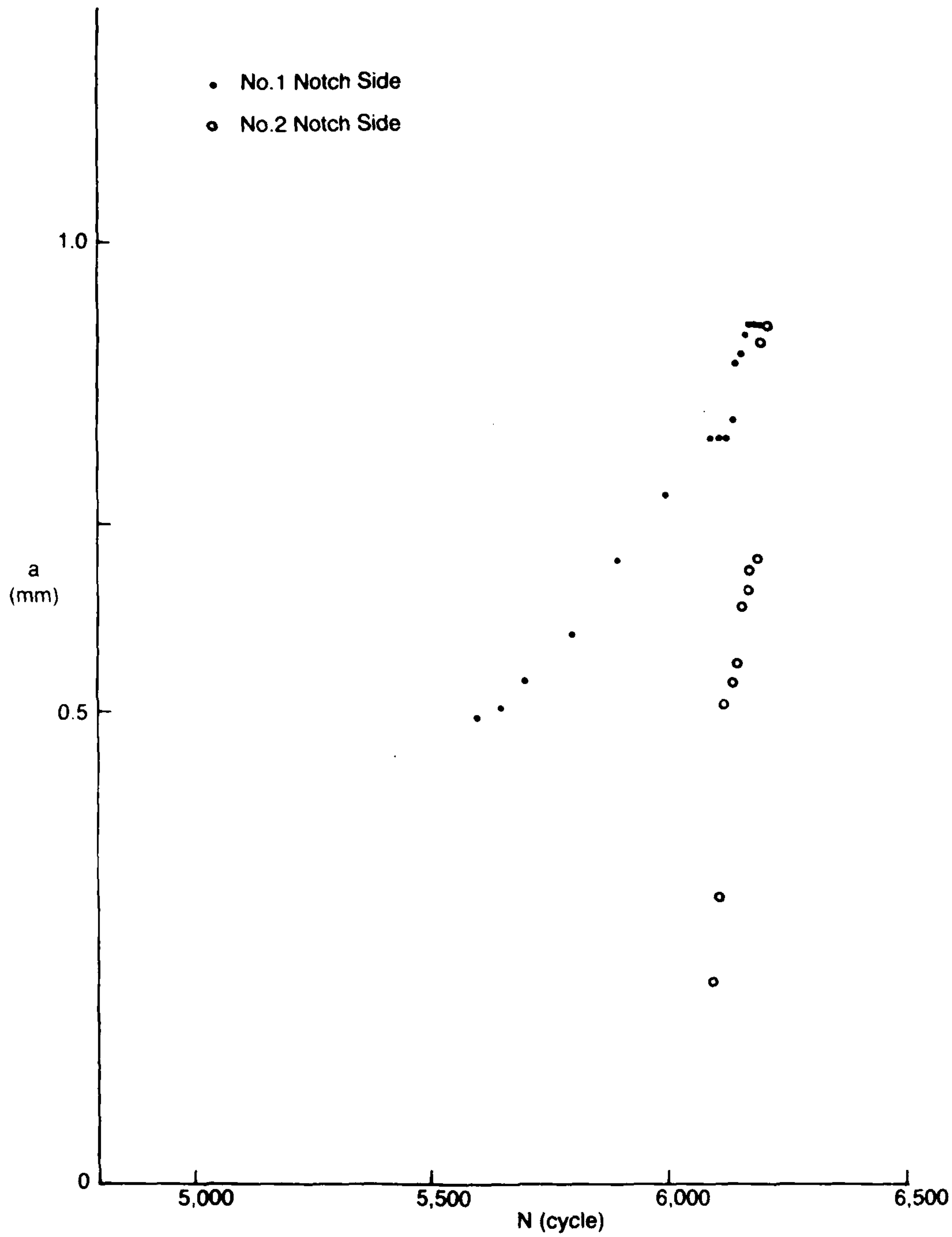



Figure 16. Change of Crack Length with Number of Fatigue Loading Cycles in Flat Double Edge Notched Specimen No. 5 ($\Delta\sigma$ = 775 MPa)

$$(V/V_O)/(V_R/V_{R_O}) = 0.6797 + 6.0719(a/w) \\ -29.8160(a/w)^2 + 57.3172(a/w)^3$$

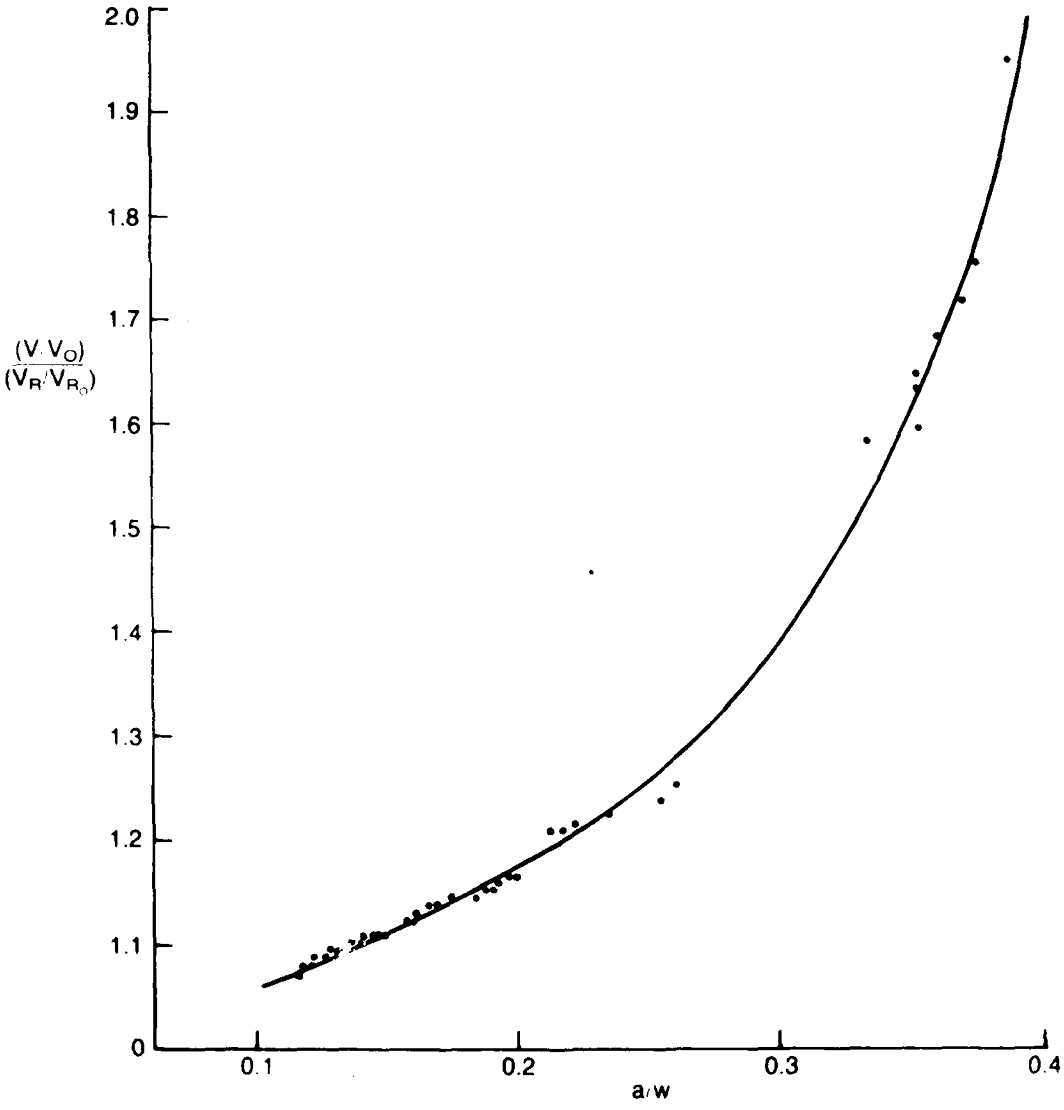



Figure 17. Change of Normalized Crack Voltage with Normalized Crack Length in Flat Double Edge Notched Specimen No. 1 ($\Delta\sigma$ = 475 MPa)

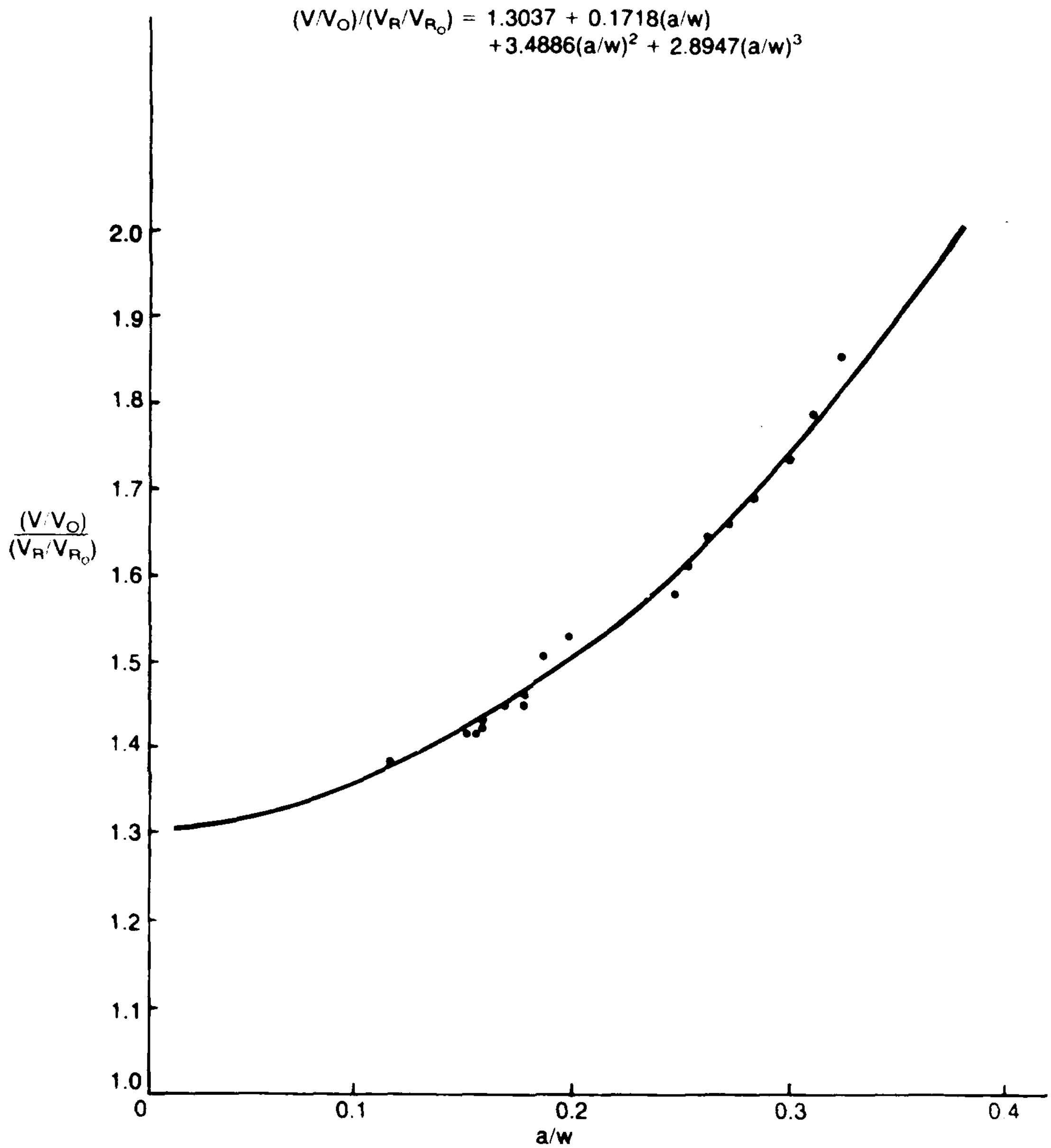



Figure 18. Change of Normalized Crack Voltage with Normalized Crack Length in Flat Double Edge Notched Specimen No. 2 ($\Delta\sigma$ = 475 MPa)

$$(V/V_O)/(V_R/V_{R_O}) = 0.9927 + 0.4226(a/w) - 3.4603(a/w)^2 + 21.8985(a/w)^3$$

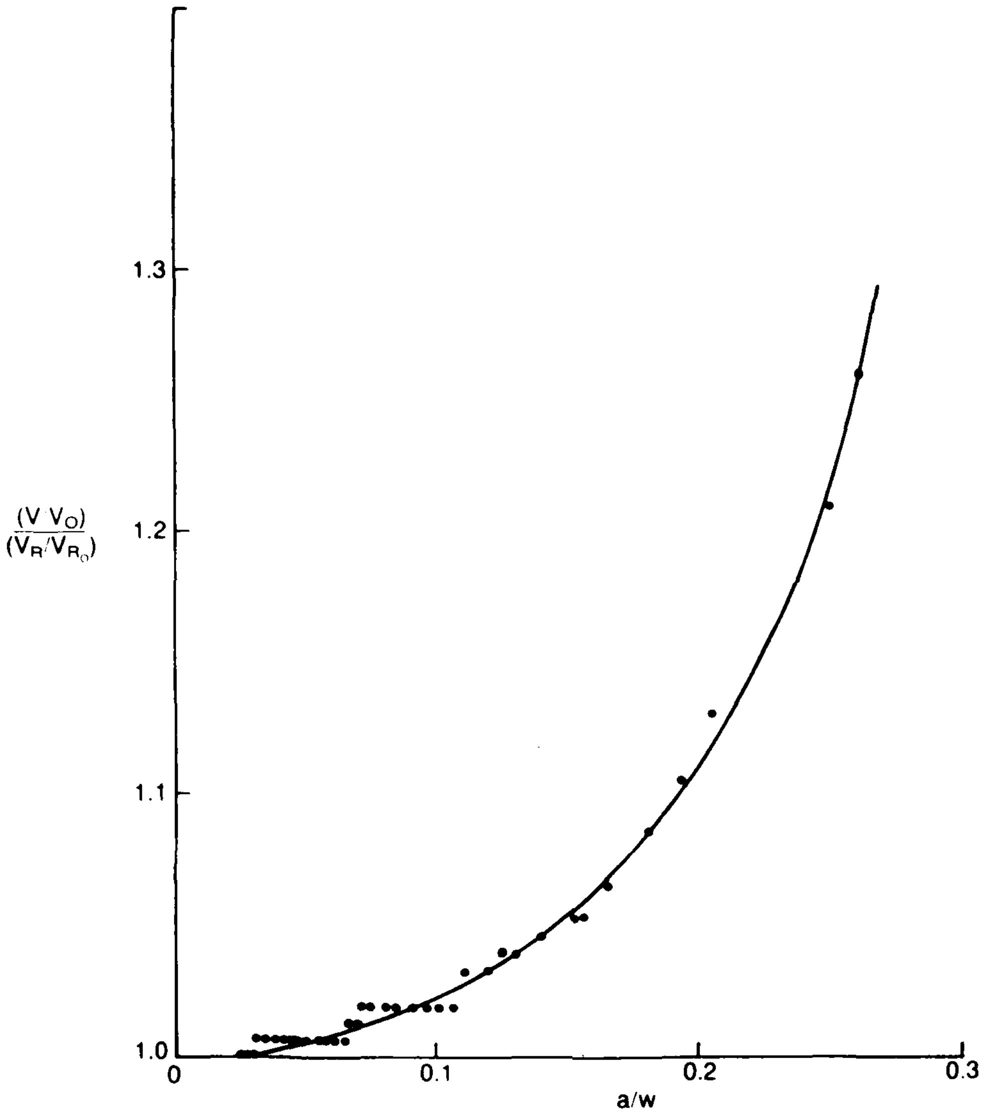



Figure 19. Change of Normalized Crack Voltage with Normalized Crack Length in Flat Double Edge Notched Specimen No. 4 ($\Delta\sigma$ = 625 MPa)

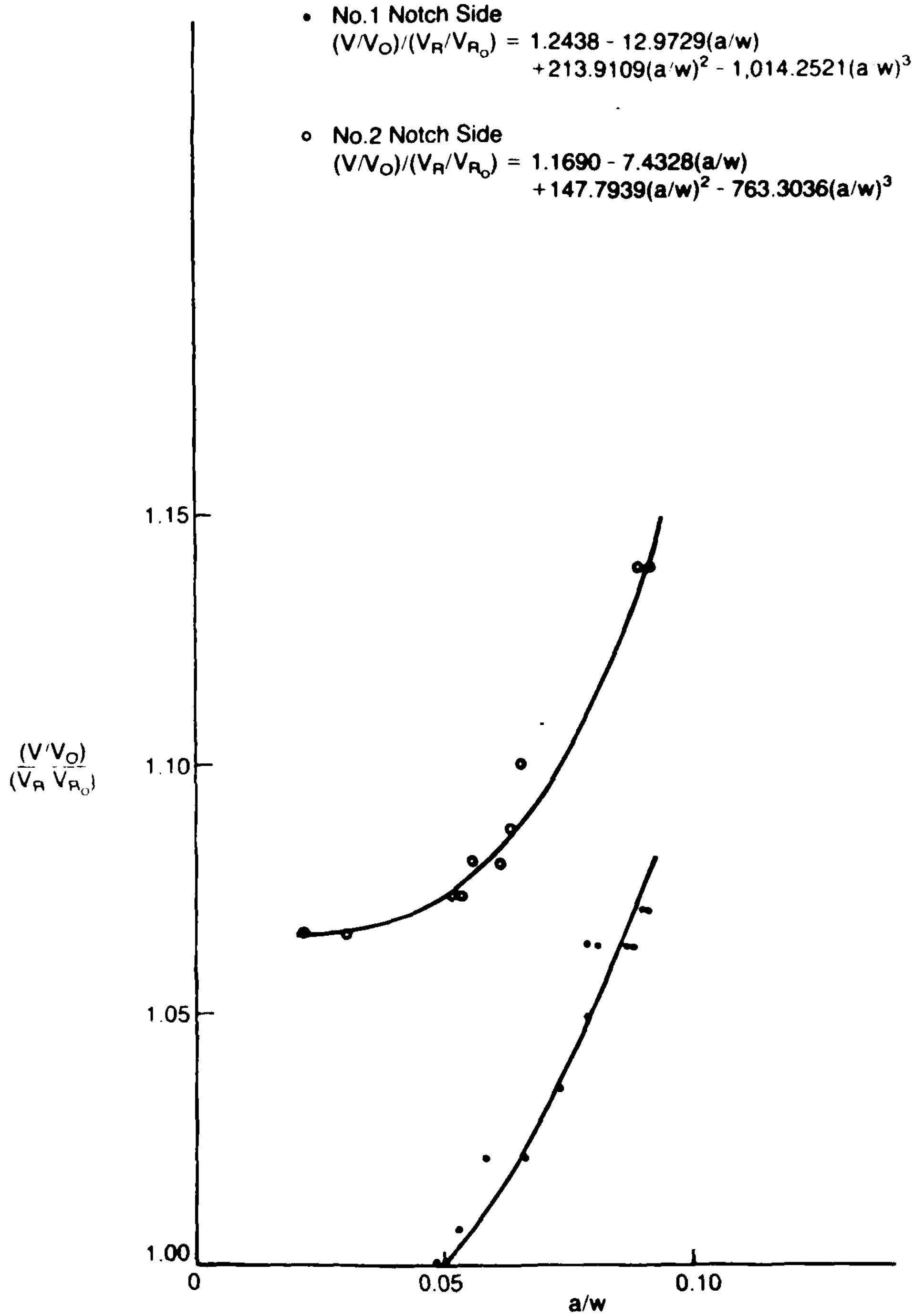



Figure 20. Change of Normalized Crack Voltage with Normalized Crack Length in Flat Double Edge Notched Specimen No. 5 ($\Delta\sigma$ = 775 MPa)

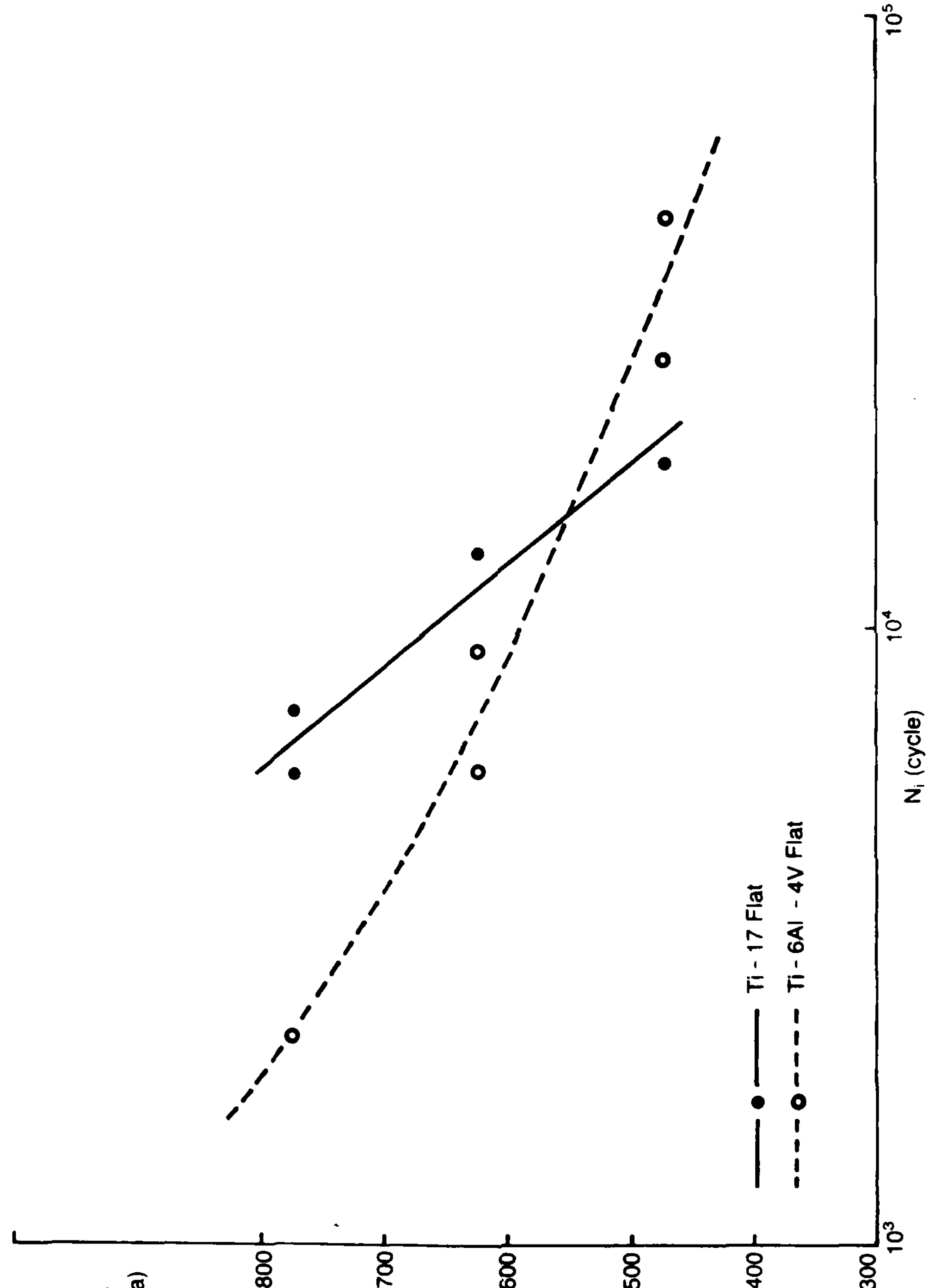



Figure 21. Applied Stress Range and Corresponding Fatigue Crack Initiation Life in Flat Double Edge Notched Specimen

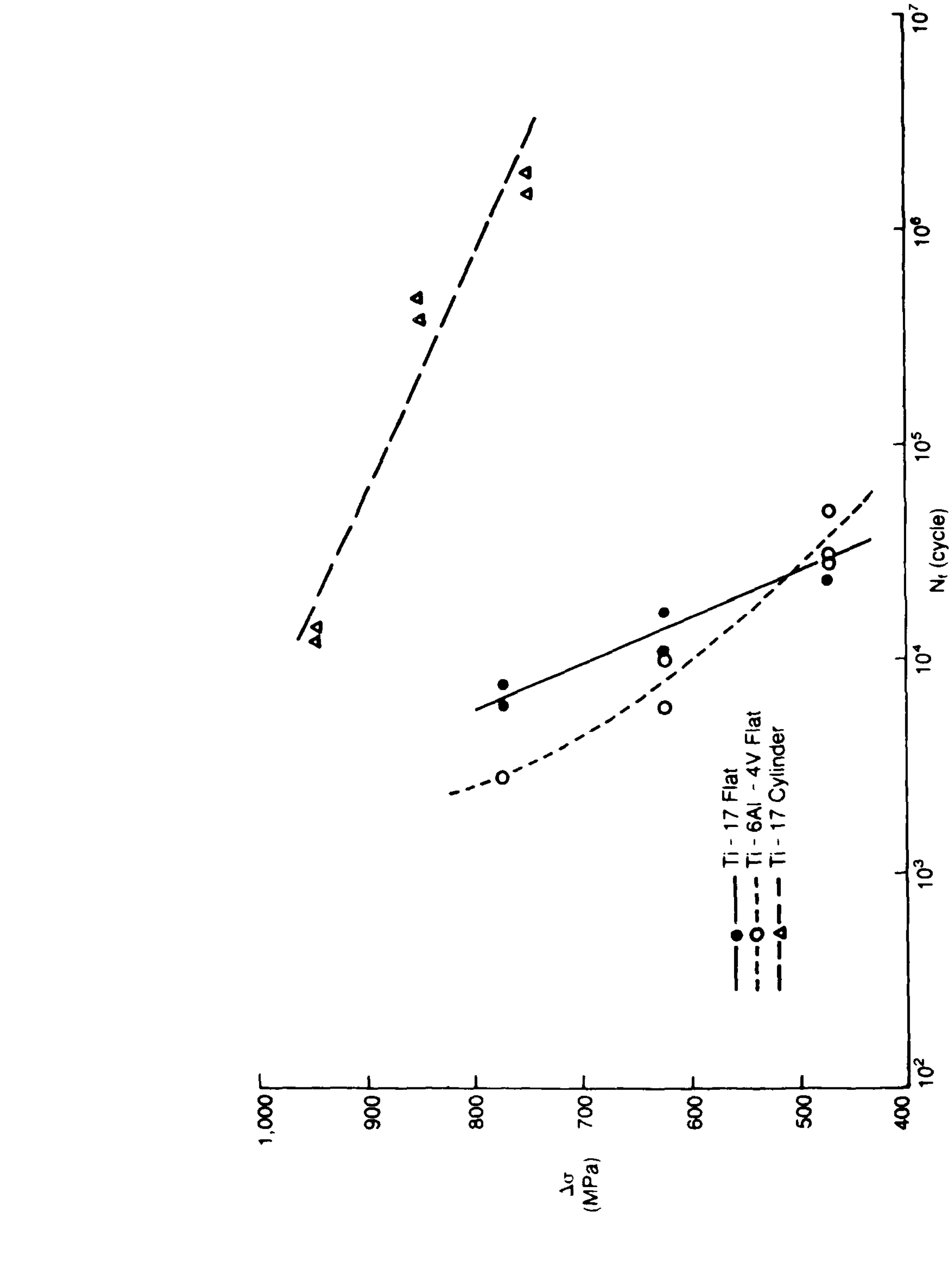
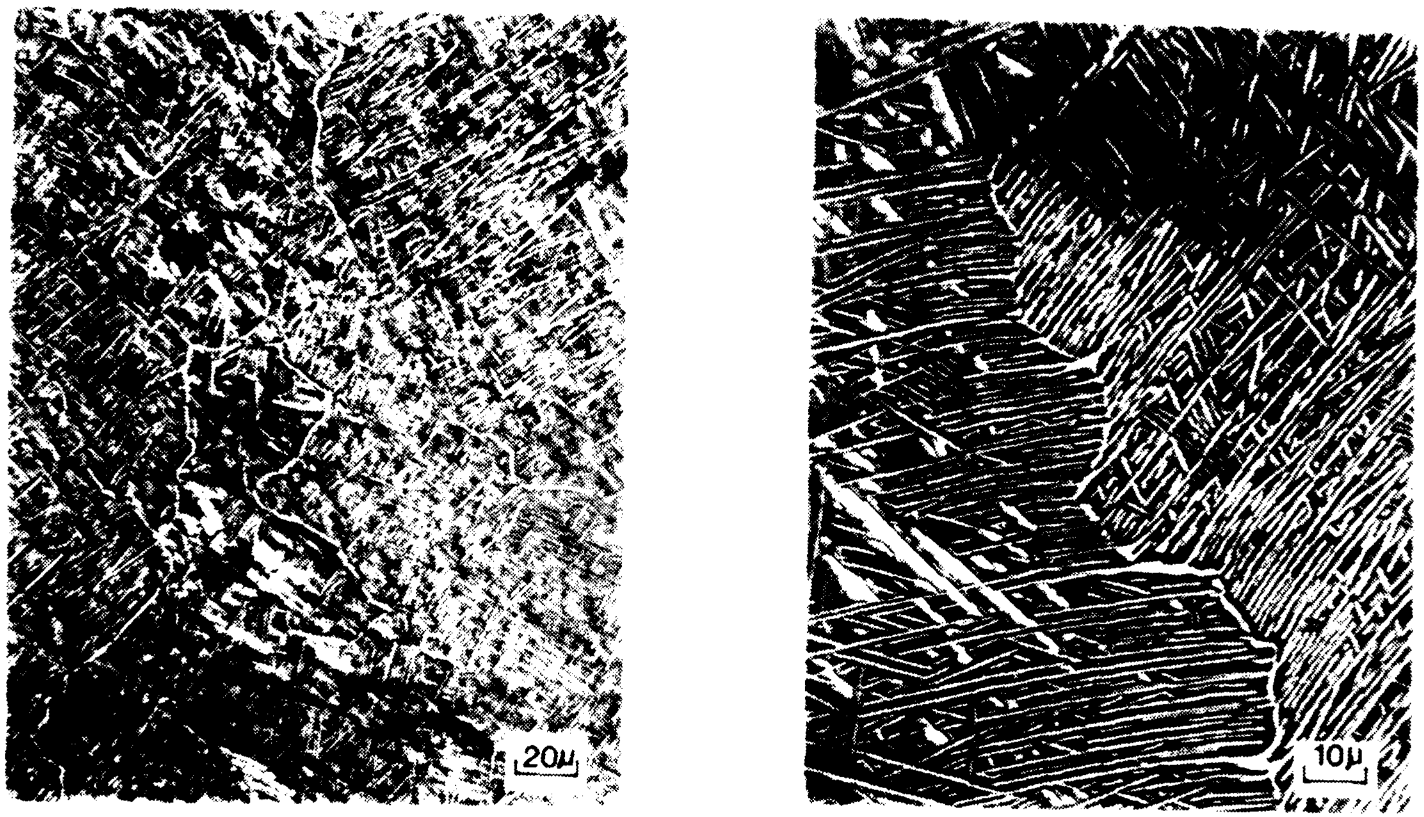



Figure 22. Applied Stress Range and Corresponding Fatigue Fracture Life in Flat Double Edge Notched Specimen




(a) (b)

Figure 23 Microstructure of Specimen Material Ti-17 Alloy
(a) Cylindrical Unnotched Specimen
(b) Flat Double Edge Notched Specimen

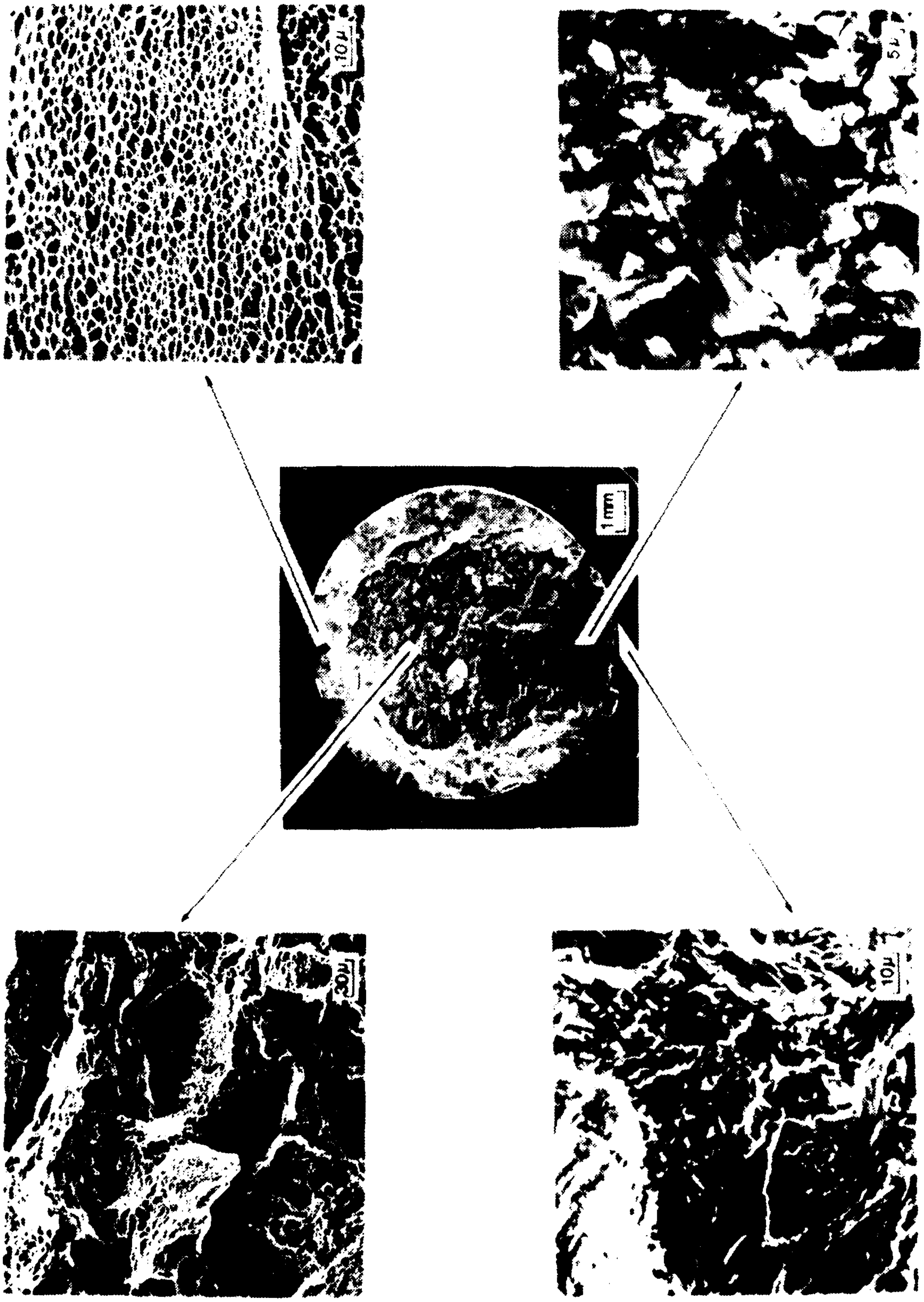



Figure 24. Fractograph of Cylindrical Unnotched Specimen

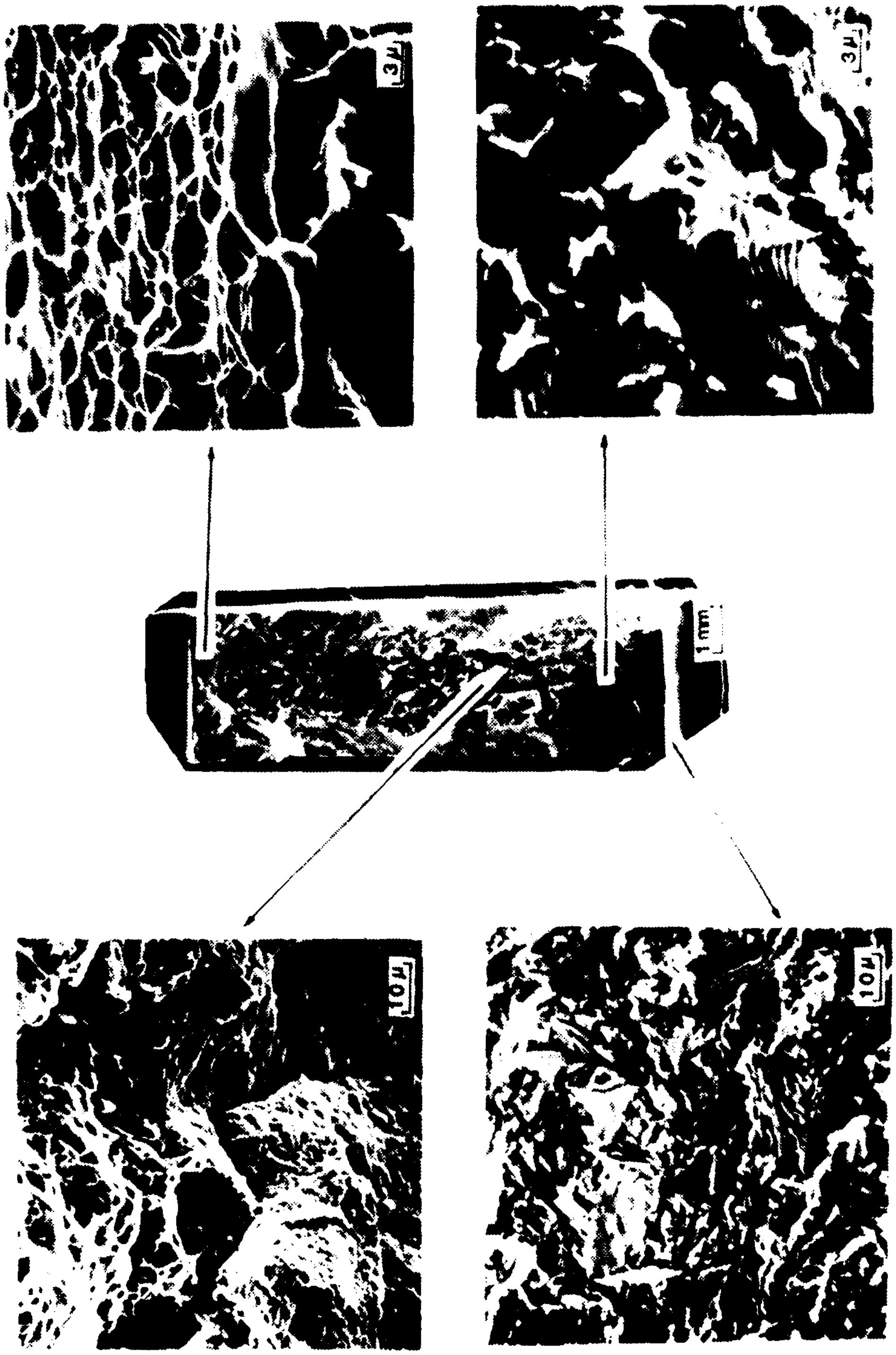



Figure 25 Fractograph of Flat Double Edge Notched Specimen

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